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Angle Of Arrival Based Indoor Localization with Cooperative MIMO Beamforming Scheme

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Abstract—We present a novel angle of arrival (AOA) based indoor localization approach in multiple-input-multiple-output (MIMO) smart antenna system. We exploit the directivity property of the smart antenna array at both transmitter and receiver sides. In contrast to conventional AOA based localization approaches, our proposed localization method combines beam steering (beamforming) transmission and receiving approach, and uses Rician fading channel model in order to simulate a more realistic environment. By setting the beamforming weights, the access point (AP) only listens to a specific direction which allows suppressing the strong signals coming from scattered paths. The angle estimation is done by analysis of the obtained angle vs. power profile. For accuracy performance analysis, we derive the expression for the location error with respect to the estimated angle of the desired user, in the presence of Rician fading. Based on the simulation results, our proposed approach provides a meter or sub-meter level accuracy and a nearly 40% decrement of location error compared to the benchmark with 4×4 array configuration.

Index Terms—Indoor localization, Beamforming, Angle of Arrival (AoA), Smart antenna

I. INTRODUCTION

The ability to accurately locate indoor users has been recently shown to be as vital for many emerging location-based applications and services. Context-aware commercial services tailor users' online experiences to their location while shopping in malls, precincts and museums. In security, location information is needed to pin-point nefarious mobile users. Location is also rapidly emerging as a feature of social networking. With the increasing use of Wi-Fi, many localization techniques based on Wi-Fi have been developed. Most of these systems employ fingerprint approach which requires an off-line training phase to obtain a signature map of signal strength or other characteristic [1]–[5]. For example, received

signal strength (RSS) [1], channel state information (CSI) [2] and CSI-MIMO [3] fingerprinting systems explore the location related signature to predict the users location. The major limitation is that they require extensive survey measurement for signature map creation before real-time localization, and the map will become unreliable if the indoor channel and environment changes with time.

With the rapid development of MIMO technique, WLAN technology based on the 802.11n standard also includes provisions for MIMO antenna configurations. Nowadays, Wi-Fi APs are already incorporating with increasing number of antenna to enhance the data throughput and propagation coverage. At the same time, several multiple antenna systems [6], [7] have been proposed for mobile phone applications. In [8], they investigate the integration of monopole-antenna arrays into handheld devices in the 5.0-GHz band and study their capability for beamforming synthesis. In [9], the first study of an important realization of directional communication, beamforming, on mobile devices is reported. It demonstrates that beam forming is already feasible on mobile devices in terms of form factor, device mobility and power efficiency. We expect that in the near future, mobile devices such as smart phones and tablets will also be equipped with multiple antennas to meet the demand for MIMO link. This gives a new opportunity for angle based indoor localization technique which can employ antenna array for angle estimation.

Some work has been undertaken to exploit using AP with multiple antennas for Angle Of Arrival (AOA) estimation based indoor localization. Array track based on MUSIC algorithm [10] and DOA system based on Beamscan algorithm [11] exploit the increasing number of antennas at APs to provide location estimation for indoor environment. But they only consider using multiple antennas at receiving AP and leave the transmitting mobile device unexploited. Spinloc [12] explores the feasibility of locating a device by deliberately inserting blockages (user's body) in wireless signal reception. The limitation is it needs the user to physically spin around at current location. Some work [13]–[15] has been undertaken to study the error of AOA based indoor localization. They focus on the comparison between different existing AOA estimation algorithms. Instead of using multiple APs, a single AP based localization system with TOA and AOA is proposed and analyzed using deterministic path loss model in [16]. All these works focus on using antenna array at receiver side to estimate the AOA which suffers from the channel fading effect. The main problem is the obtained AOA spectra will contains noise components coming from scattered paths. Furthermore, these

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published works only consider using deterministic raytracing channel model or field experiment to evaluate the performance of their approaches. These reported results are site-dependent and may vary in different indoor environments. The statistic channel model is mainly used in published fingerprinting based work and only based on path loss model. To the best of our knowledge, very few work provides the performance analysis and evaluation against the fading channel effect. In this paper, we adopt statistic Rician fading channel model for our indoor localization investigation in a more general and realistic environment.

In this work, our approach exploits the beam steering at both transmitter and receiver sides. Evaluation and analysis of the proposed approach in a fading channel condition is also provided. A novel angle-base indoor localization approach with cooperative MIMO smart antenna system in Rician fading channel is proposed. Transmitter shares direction of emission information with APs which estimate the angle of arrival and carry out the triangulation. The main contributions are:

- Different from the previous published work which only consider using multiple antennas at AP and path loss channel model, we propose and analyze a new angle-based indoor localization approach in MIMO smart antenna system in fading channel, which can represent a more realistic environment.
- We provide the closed form expression for the angle and location estimation with presence of fading.
- Performance analysis and numerical studies are provided to evaluate the accuracy of the proposed method with the metric of location error in distance.

The rest of the paper is organized as follow. In section II, we introduce the system model and relevant algorithms. This is followed by the performance analysis of the proposed localization method in Section III. Simulation evaluation and numerical results of the proposed system are presented in Section IV. Finally, conclusions are given in section V.

II. SYSTEM MODEL

As shown in Fig. 1, the 2-D localization system contains two types of nodes, AP and Mobile Device (MD). The 4 APs at corners, whose positions are pre-known, receive the signal from the MD which is the target of localization. In order to locate the MD, each AP needs to estimate the angle (bearing or direction) between the MD (target) and themselves. We assume that both APs and MD are embedded with a digital compass and able to refer to the true East as a reference direction 0° . Here, the true angle between the MD and j -th AP is defined by θ_j which is the angle between direction from MD to AP and the True East in anticlockwise. After that, the 4 APs will use the estimated angles and their known location information to perform triangulation to estimate the position of the MD. It is also assumed that MD is equipped with an antenna array and has the ability to steer the transmit beam to any direction α from 0° to 360° in anticlockwise (true North, West and South are 90° , 180° and 270°), named Direction of Emission (DOE), whilst each AP is incorporating with an uniform linear array

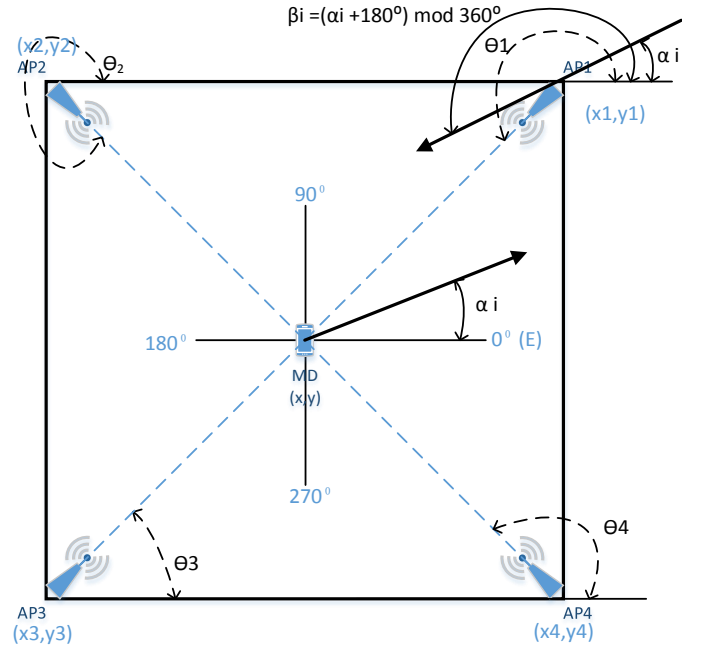


Fig. 1. Multiple APs localization model

with M elements and has the ability to listen to a specific direction for each DOE α_i .

A. Channel Model

Rather than a pure Line-Of-Sight (LOS) channel case, we adopt Rician channel model, a more generic and realistic channel condition model [17], [18], to analyze and evaluate our system. Compared to deterministic channel model (e.g. Raytracing), statistic Rician channel model can be applied to a much broader environment and widely used in wireless communications.

Considering a single AP case as Fig. 2, there is a transmitter MD with N transmitting antennas and a receiver AP_j with M receiving antennas. For this $M \times N$ MIMO channel, the channel matrix is given by

$$\mathbf{H}_j = \sqrt{(K/(K+1))} \mathbf{H}_{0,j} + \sqrt{(1/(K+1))} \mathbf{H}_{r,j} \quad (1)$$

where $\mathbf{H}_{0,j}$ is LOS component and $\mathbf{H}_{r,j}$ is the scattered component represented by a matrix with i.i.d circularly-symmetric complex Gaussian random variables with zero mean and unit variance. It is assumed that $k > 0$, where K is the Rician K -factor. According to the location of MD and AP_j , $\mathbf{H}_{0,j}$ can be written as

$$\mathbf{H}_{0,j} = \mathbf{r}_{0,j}^T \mathbf{g}_{0,j} \quad (2)$$

where \mathbf{r}_0 and \mathbf{g}_0 are the array response at AP_j and MD, respectively, which are given by

$$\mathbf{r}_{0,j} = [1, \dots, \exp(j(M-1)\tau_{AP_j} \cos \theta_{AP_j})], \quad (3)$$

$$\mathbf{g}_{0,j} = [1, \dots, \exp(-j(N-1)\tau_{MD} \cos \theta_{MD_j})], \quad (4)$$

where $\tau_{AP_j} = 2\pi p_{AP_j}/\lambda$ and $\tau_{MD} = 2\pi p_{MD}/\lambda$. p_{AP_j} and p_{MD} is the space between antenna elements at AP_j and MD.

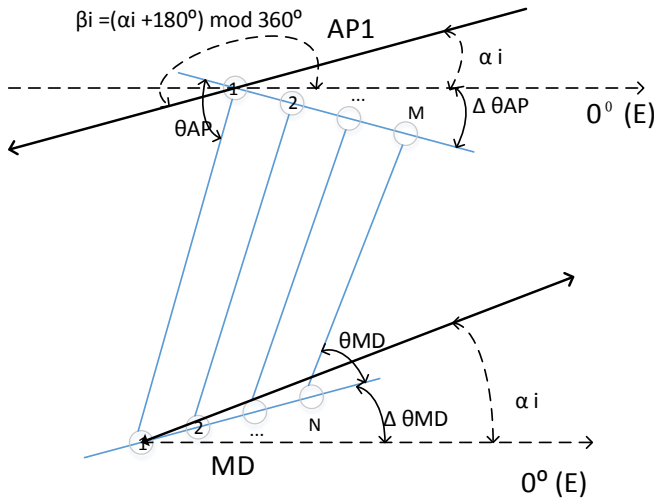


Fig. 2. Illustration of MIMO channel model

λ is wave length. And θ_{MD_j} and θ_{AP_j} is the angles from LOS direction to MD array plane and AP_j array plane. The received signal at AP_j is given by

$$\mathbf{y}_j = \sqrt{PL(d_j)} \mathbf{H}_j \mathbf{b} x + \mathbf{n} \quad (5)$$

where $PL(d_j)$ is the pathloss component of the channel given by $PL(d_j) = (c/(4\pi f_0 d_0))^2 (d_0/d_j)^n$. f_0 is the carrier frequency, d_j is the distance between MD and AP_j , d_0 is a reference distance (i.e. $d=1$ meter) and n is the pathloss exponent of the channel. \mathbf{b} is a normalized beamformer (i.e. $\|\mathbf{b}\|=1$), x is the transmitting signal with constant power P_x (i.e. $|x|^2 = P_x$) and \mathbf{n} is the AWGN vector of the channel with zero mean and variance matrix $\sigma^2 I_M$ (i.e. $\mathbf{n} \sim \mathcal{CN}(0, \sigma^2 I_M)$).

B. Proposed Localization Method

1) *DOE sharing process*: The first stage is DOE sharing process. The MD broadcasts the DOE information $\alpha_i ([0^\circ, 360^\circ])$ to all 4 APs, but only the AP_j ($\alpha_i \in \{AP_j\}$) will send a feedback to MD and then set the array weights to listen to a the direction β_i where $\beta_i = (180^\circ + \alpha_i) \bmod 360^\circ$. AP_j will only react to a specific set S_j of DOE α_i that is given by

$$S_j = \{(j-1) * 90^\circ, j * 90^\circ\}, \quad (j = 1, 2, 3 \text{ and } 4). \quad (6)$$

2) *Power measurement process*: The second stage is the power measurement process. After the MD gets the feedback from AP_j , MD steers the beam to DOE α_i . For each DOE α_i , beam steering vector $\mathbf{b}(\alpha_i)$ is given by

$$\mathbf{b}(\alpha_i) = \frac{1}{\sqrt{N}} [1, \dots, \exp(j(N-1)\tau_{MD} \cos(\alpha_i - \Delta\theta_{MD}))]^T. \quad (7)$$

The array combining vector $\mathbf{a}(\alpha_i)$ at AP_j ($j=1,2,3$ and 4) is given by

$$\mathbf{a}_j(\beta_i) = \frac{1}{\sqrt{M}} [1, \dots, \exp(j(M-1)\tau_{AP} \cos(\beta_i - \Delta\theta_{AP}))] \quad (8)$$

$\mathbf{a}_j(\beta_i)$ is used to adjust the receiving array pattern to a specific direction β_i which means the AP_j is listening from the direction β_i , where $\beta_i = (180^\circ + \alpha_i) \bmod 360^\circ$. It is noted that East is set as the reference direction 0° . And the angle in anticlockwise is positive and clockwise is negative. Therefore, in Fig. 2, $\Delta\theta_{MD}$ is positive and $\Delta\theta_{AP}$ is negative. And these bias angles from East are assumed to be known by themselves with their embedded compass. The output signal power at the receiving antenna array for α_i at AP_j is given by

$$P_j(\alpha_i) = |\mathbf{a}_j(\beta_i) * \mathbf{y}_j(\alpha_i)|^2. \quad (9)$$

3) *Angle estimation process*: The third stage is the angle estimation process. After the AP_j gets the power $P_j(\alpha_i)$, it will reset the array weights and send a feedback to tell MD that $P(\alpha_i)$ is recorded. After MD receives the ACK for α_i from AP_j , the previous 2 processes will be repeated for next DOE α_{i+1} until P values are recorded for all DOE α . At each AP_j , it will obtain the profile of P against α_i ($\alpha_i \in S_j$) and pick the α_i with the highest P value to calculate the estimated angle θ'_j between AP and MD. For each AP_j , the estimated angle θ'_j is given by

$$\theta'_j = (\arg\max_{\alpha_i} (P_j(\alpha_i) | \alpha_i \in S_j) + 180^\circ) \bmod 360^\circ. \quad (10)$$

4) *Triangulation process*: The final stage is triangulation process, which uses the estimated angles θ'_j to calculate the coordinate of MD with unknown location (x_{MD}, y_{MD}) . Denoting the true angles θ_j between MD and AP_j with the pre-known 2-D coordinate (x_j, y_j) , it is straightforward to have that

$$\tan \theta_j = \frac{y_j - y_{MD}}{x_j - x_{MD}}, \quad (j = 1, 2, 3 \text{ and } 4) \quad (11)$$

From (11), we can further have

$$\sin \theta_j (x_j - x_{MD}) = \cos \theta'_j (y_j - y_{MD}), \quad (j = 1, 2, 3 \text{ and } 4). \quad (12)$$

Therefore,

$$-x_{MD} \sin \theta_j + y_{MD} \cos \theta_j = -x_j \sin \theta_j + y_j \cos \theta_j \quad (j = 1, 2, 3 \text{ and } 4). \quad (13)$$

With the knowledge of the estimated angle θ'_j from (10), the estimated location (x_0, y_0) of the MD can be obtained from,

$$(x_0, y_0) = \arg\min_{(x,y)} (|Q|, \forall j). \quad (14)$$

where $Q = (-x \sin \theta'_j + y \cos \theta'_j) - (-x_j \sin \theta'_j + y_j \cos \theta'_j)$ ($j = 1, 2, 3$ and 4)

III. PERFORMANCE ANALYSIS

A. Closed-form Expression for Angle Estimation with Fading

In the proposed approach, we use the angle α_i with the maximum $P_j(\alpha_i)$ as a indicator to estimate the angle θ_j between MD and AP_j . To verify the criteria for angle estimation in (10), we firstly analyze the mathematical relationship between α_i and $P_j(\alpha_i)$. The output signal power P_j at the receiving antenna array for α_i is given by

$$\begin{aligned} P_j(\alpha_i) &= |\mathbf{a}_j(\beta_i) * \mathbf{y}_j(\alpha_i)|^2 \\ &= |\mathbf{a}_j(\beta_i) * (\sqrt{PL(d_j)} \mathbf{H}_j \mathbf{b}(\alpha_i) x)|^2 + P_n \end{aligned} \quad (15)$$

In (15), the first element is related to the power of signal component and P_n is combined noise elements with an expectation of $E(P_n) = \sigma^2$. Furthermore, the $P_j(\alpha_i)$ can be rewritten as

$$P_j(\alpha_i) = P'_j(\alpha_i) + P_N. \quad (16)$$

Where $P'_j(\alpha_i) = PL(d_j)P_x |\mathbf{a}_j(\beta_i) \sqrt{\frac{K}{K+1}} \mathbf{H}_0 \mathbf{b}(\alpha_i)|^2$ is the deterministic power components from LOS signal as a function of α_i and the latter part $P_N = P_{nlos} + P_n$, where P_{nlos} is random component coming from scattered path with an expectation of $E(P_{nlos}) = \frac{PL(d_j)P_x}{K+1}$, can be regarded as a random noise component. Assuming the $P'_j(\alpha_i)$ is the dominate component in (16), then we can have

$$\alpha'_j = \argmax_{\alpha_i} (P'_j(\alpha_i)) \approx \argmax_{\alpha_i} (P_j(\alpha_i)), \alpha'_j \in \{\alpha_i\}. \quad (17)$$

Therefore, to find the α_i maximize $P_j(\alpha_i)$ is approximately to find the α_i maximize $P'_j(\alpha_i)$. $P'_j(\alpha_i)$ can be further derived as

$$\begin{aligned} &\frac{PL(d_j)P_x K}{K+1} \frac{1}{MN} \sum_{m=1}^M \sum_{p=1}^M \exp(j(m-p)\phi) \sum_{n=1}^N \sum_{q=1}^N \\ &\exp(j(n-q)\omega) \\ &= \frac{PL(d_j)P_x K}{K+1} \frac{1}{MN} [2(\cos((M-1)\phi) + \dots + (M-1) \\ &\cos \phi) + M][2(\cos((N-1)\omega) + \dots + (N-1)\cos \omega) + N], \end{aligned} \quad (18)$$

where ϕ and ω are denoted as $\tau_{AP_j}(\cos \theta_{AP_j} - \cos(\alpha_i - \Delta \theta_{AP_j}))$ and $\tau_{MD}(\cos(\alpha_i - \Delta \theta_{MD_j}) - \cos \theta_{MD_j})$. It is straightforward that (18) will reach the maximum value when ϕ and ω are equal to 0. As a result,

$$\alpha'_j = \theta_{AP_j} + \Delta \theta_{AP_j} = \theta_{MD_j} + \Delta \theta_{MD_j}. \quad (19)$$

We can further prove that

$$\theta_j = (\alpha'_j + 180^\circ) \bmod 360^\circ \quad (20)$$

With (17), θ_j in (20) can be further written as

$$\theta_j \approx (\argmax_{\alpha_i} (P_j(\alpha_i)) + 180^\circ) \bmod 360^\circ = \theta'_j, \quad (21)$$

Hence, θ'_j obtained from the criteria in (10) can be used for angle of arrival θ_j estimation.

B. Estimated Location of Triangulation with Fading

Because of the estimation error within θ'_j , it could be no solution for (14). which means the estimated directions from 4 APs do not intersect in one point. However, an approximated solution can still be found from the over-determined equation system. (14) can be written in matrix from as

$$Cu = z, \quad (22)$$

where

$$u \in \mathbb{R}^{2 \times 1} = [x_0 \ y_0]^T, \quad (23)$$

$$C \in \mathbb{R}^{4 \times 2} = \begin{pmatrix} -\sin \theta'_1 & \cos \theta'_1 \\ \vdots & \vdots \\ -\sin \theta'_4 & \cos \theta'_4 \end{pmatrix}, \quad (24)$$

and

$$z \in \mathbb{R}^{4 \times 1} = \begin{pmatrix} -x_1 \sin \theta'_1 + y_1 \cos \theta'_1 \\ \vdots \\ -x_4 \sin \theta'_4 + y_4 \cos \theta'_4 \end{pmatrix}. \quad (25)$$

Moore-Penrose pseudo inverse is taken on the both side to get the estimated location u as

$$u = (C^T C)^{-1} (C^T z). \quad (26)$$

After further mathematical manipulation, the closed-form expression of estimated MD position (x_0, y_0) is given by

$$x_0 = \frac{\|c_2\|^2 c_1^T z - c_2^T c_1 c_2^T z}{\|c_1\|^2 \|c_2\|^2 - c_1^T c_2 c_2^T c_1} \quad (27)$$

$$y_0 = \frac{-c_1^T c_2 c_1^T z + \|c_1\|^2 c_2^T z}{\|c_1\|^2 \|c_2\|^2 - c_1^T c_2 c_2^T c_1} \quad (28)$$

where $c_1 = [-\sin \theta'_1, -\sin \theta'_2, -\sin \theta'_3, -\sin \theta'_4]^T$ and $c_2 = [\cos \theta'_1, \cos \theta'_2, \cos \theta'_3, \cos \theta'_4]^T$.

To measure the accuracy of proposed approach, location error (LE) is used in our performance evaluation, which are defined as

$$LE = \sqrt{(x_0 - x_{MD})^2 + (y_0 - y_{MD})^2}. \quad (29)$$

LE is the distance (in meter) between estimated location (x_0, y_0) and true location (x_{MD}, y_{MD}) of the target MD.

IV. SIMULATION ANALYSIS

Matlab simulation has been carried out to evaluate the performance of the proposed localization method. The 2-D evaluation scenario includes 4 APs placed at the corners of a $10m \times 10m$ space. The 2-d coordinate (x_j, y_j) of AP 1-4 is (10, 10), (0, 10), (0, 0) and (10, 0), and the tested MD is placed at (4, 6). Both the MD and AP are considered to be equipped with a Uniform Linear Array (ULA) with a half wavelength inter-element space. The number of the antenna elements are varied from 4, 6 to 8 in order to show the impact of different antenna number on localization accuracy. The signal-to-noise

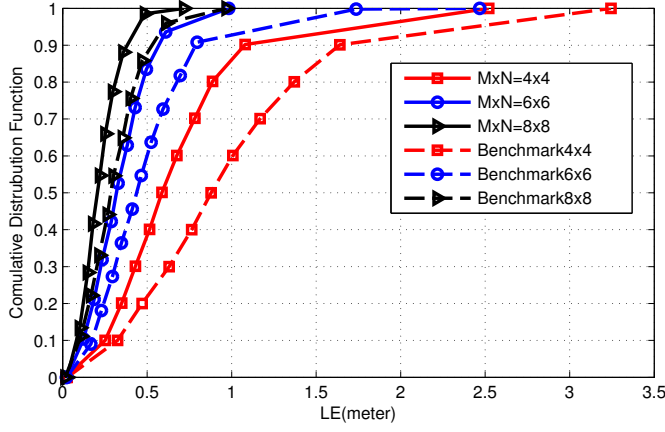


Fig. 3. CDFs of location error of proposed approach and benchmark depending on number of antennas, $K=1$, $\text{SNR}=10\text{dB}$

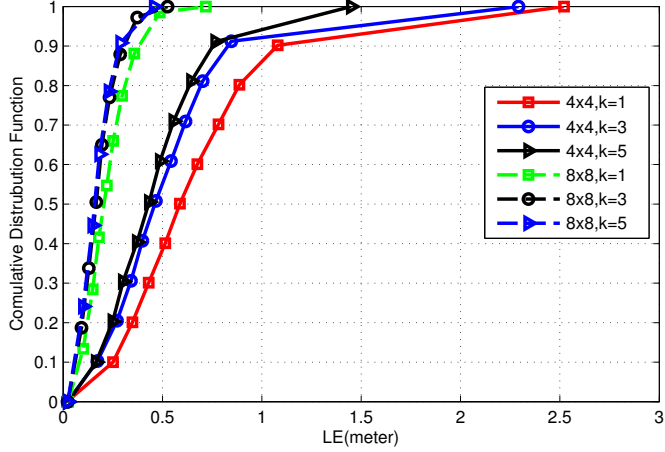


Fig. 4. CDFs of location error of proposed approach depending on Channel Rician K factors, $\text{SNR}=10\text{dB}$

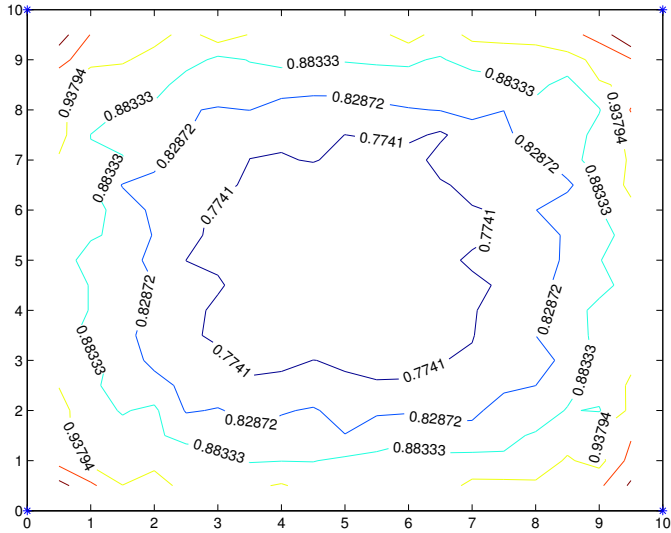


Fig. 5. Contour plot of location error of proposed approach with $K=1$ and $\text{SNR}=10\text{dB}$

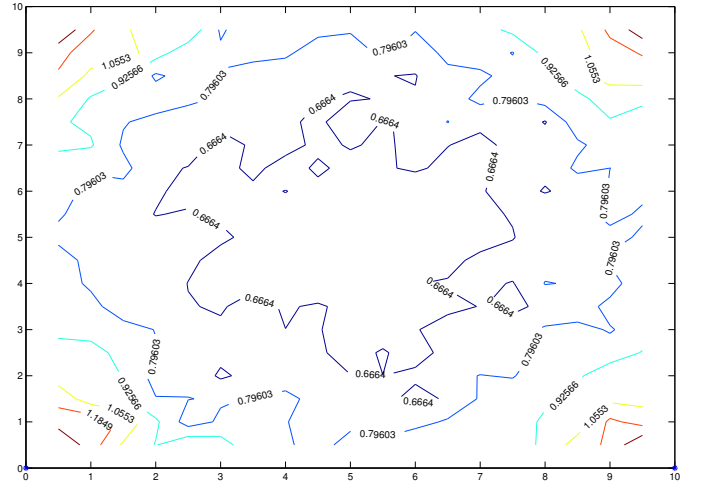


Fig. 6. Contour plot of location error reduction of the proposed approach compared to benchmark with $K=1$ and $\text{SNR}=10\text{dB}$

ratio (SNR) is set to be 10 dB and the value of Rician K factor is set as 1, 3 and 5 (0dB, 5dB and 7 dB) [19], [20] to explore the system robustness against the Rician fading effect. $K = 1$ indicates equal power between LOS and NLOS which would be a complex environment with moving pedestrians, $K = 3$ would be a typical office or home environment and $K = 5$ would be a more open space such as shopping mall.

LE is used to evaluate the accuracy of the proposed approach. The results in the following figures for each array configuration and K factor are obtained over 1000 independent simulation runs. In each run, MD steers the DOE from 0° to 360° with a step of 1° , which involves 360 transmissions (one channel realization per transmission) in total. And four APs calculate the estimated angle with (21) and then obtain the estimated location with (27) and (28). As the benchmark, we use the localization results with average antenna power (AAP), which means each AP uses the average power over all receiving antenna elements to perform the angle estimation instead of $P(\alpha_i)$, where $\text{AAP}(\alpha_i) = (Pr_1(\alpha_i) + \dots + Pr_m(\alpha_i) + \dots + Pr_M(\alpha_i))/M$ and $Pr_m(\alpha_i)$ is the receiving power at m th receiving antenna for DOE α_i .

The cumulative distribution function (CDF) of the LE for the given MD location depending on different number of antenna elements is shown in Fig. 3. We observe that LE is smaller in a larger number of antenna $M \times N$. When $M \times N = 4 \times 4$ which means both MD and APs are incorporated with a 4-element ULA, our proposed localization method can achieve a LE below around 1 meter for 90% of cases. For 90% of cases with $M \times N = 8 \times 8$ configuration, it achieves a LE lower than 0.35 meter. Compared to benchmark with the same 4×4 configuration, the proposed approach decreases the LE over 0.3 meter and 0.6 meter (nearly 40% decrement of LE) for 50% and 90% of cases.

Fig. 4 shows the cumulative distribution function (CDF) of the LE for the given MD location depending on different channel conditions by varying Rician K factor. We observe that

LE is smaller in larger K factor with same array configuration. When $K = 1$ which means equal power between LOS and scattered paths, our proposed localization approach with 4×4 configuration achieves nearly one meter accuracy for 90% of cases. When K factor increases to 5, which means LOS power is stronger than scattered paths, it can achieve a LE lower than 0.75 meter. In addition, when the K factor varies from 5 to 1, increment of LE level for 90% of cases is 0.2 meter smaller with 8×8 compared to that with 4×4 . Therefore, increasing the number of antenna improves the system robustness to the fading channel.

The contour plot of the location estimation error of the proposed approach within a 10m by 10m space is given in Fig. 5. Instead of fixing the MD at location (4, 6), the MD moves from one point to another with a half meter interspace (in total 361 test locations). The location estimation error is calculated over 2000 runs of simulation tests at each MD location. It is observed that when the MD is placed in the centre section of the room, the proposed approach gives the best accuracy about 0.78m location estimation error. It is also found that as the MD is moved away from the centre, the estimation error increases and reaches the worst scenario about 0.94m error near the boundary area. The reason is when the MD is near the boundary, it would be relatively far away from some of the APs giving imprecise angle estimation, which would further increase the location estimation error. For further comparison between the benchmark and proposed approach, Fig. 6 shows the contour plot of the location error reduction between the proposed approach and the benchmark. It is found that the maximum error reduction is at the boundary and corner area, which means the proposed approach would significantly reduce the estimation error (over 1m (50%) error decrease) at the worst scenario and improve the localization accuracy and performance.

The prior AOA based indoor localization work, Arraytrack [10], evaluates its system accuracy at a typical office environment. It reports that it measures 90% of cases within 3m, 1.5m and 0.9m location error with six 16-antenna, 12-antenna and 8-antenna receiving APs respectively. Compared to the accuracy of our proposed approach in a complex environment ($K=1$), we can achieve 90% of cases within 1.1m, 0.6m and 0.35m location error with 4×4 , 6×6 and 8×8 system configurations by four APs respectively, which is a over 250% improvement with even less APs.

V. CONCLUSION

In this paper, we investigated a novel angle-based indoor localization approach using cooperative MIMO smart antenna system with fading channel. Our proposed localization approach takes the advantage of the smart antenna at both MD and AP sides. In the presence of fading, the angle estimation is done by analysis of the DOE vs. power profile and the estimated location is obtained by triangulation with estimated angle from four APs. The closed form expressions for the angle and location estimation with presence of fading have been derived to evaluate the accuracy of the proposed method.

It has been shown that our proposed approach provides a meter or sub-meter level accuracy in the environment which can be applied by Rician fading channel model and a nearly 40% decrement of location error compared to the benchmark with 4×4 array configuration. It is also found that increasing the number of antenna elements will improve the system robustness against the fading effect.

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